

# Searching for Gamma-Ray Emission from Reticulum II by Fermi-LAT

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A few new dwarf spheroidal satellites (dSphs) were discovered by the Dark Energy Survey (DES). These dSphs provide new candidates for gamma-ray emission search from dark matter annihilation. These candidates have been surveyed by the Fermi-LAT, but no significant gamma-ray signature has been found, except only slight excess from some new dSphs. Reticulum II is one of such objects. In the work we reanalyze the Fermi-LAT about 7-years data at the direction of Reticulum II. In our analysis we model Reticulum II as a spatially-extended source, with different degrees of extension. We find different spatial extension may result in different TS values. But no significant gamma-ray signature over background is found in our analysis. Then we give the upper limits on the dark matter annihilation cross section from Fermi-LAT observation.

## I. INTRODUCTION

Many astrophysical and cosmological observations have shown that cold dark matter (DM) occupies 25.8% of the Universe, while the baryons only occupy 4.8%, and the rest is dark energy [1]. A potential candidate for cold DM is the so-called weakly interacting massive particle (WIMP) [2–4]. WIMPs can annihilate or decay to protons/antiprotons, electrons/positrons, and  $\gamma$ -rays etc., which applies an indirect way to search for DM signals. An excess of electrons and positrons have been observed by PAMELA [5] and AMS02 [6]. This anomalous excess may be produced by DM annihilation, but it is hard to confirm because the charged particles are deflected by the magnetic fields and the propagation is complex. Therefore, compared with charged particle,  $\gamma$ -ray is a better approach to investigate DM.

WIMPs annihilation can directly produce  $\gamma$ -rays, or indirectly produce  $\gamma$ -rays through the cascade decay, final state radiation, and inverse Compton scattering process. These  $\gamma$ -rays should be mainly generated in the regions with high DM density, and then be captured by the detectors, such as the space-borne  $\gamma$ -ray detector Fermi Large Area Telescope (Fermi-LAT) [7]. Many works have finished to investigate the  $\gamma$ -rays in some astrophysical objects with high DM density, for instance, the Galactic halo [8–14], galaxy clusters [15], and Galactic DM substructures [16–18]. In the Galactic center, the  $\gamma$ -ray excess [10, 19–24] origin from DM annihilation is still unconfirmed, because there are too many astrophysical sources causing a complicated backgrounds. But the nearby dwarf spheroidal satellites (dSphs) are the ideal candidates in probing  $\gamma$ -rays from DM annihilation because on the one hand they have high DM density and on the other hand they are lack of conventional astrophysical  $\gamma$ -ray sources [25, 26].

More than twenty dSphs have been discovered by the Sloan Digital Sky Survey (SDSS) [27], which has a deep

and systematic coverage on the northern celestial hemisphere. Numerous studies have been performed to search for  $\gamma$ -ray emission among thees dSphs, but no significant signal has been found [28–34]. As a southern-hemisphere optical instrument, the ongoing Dark Energy Survey (DES) [35], has released 16 new dSphs in 2015 [36–38]. Some works have been done in searching for  $\gamma$ -ray emissions among these new candidates by Fermi-LAT. No significant signal has been found, except two candidates Reticulum II and Tuc III, showing a very weak suspected  $\gamma$ -ray GeV excess [39–42]. But there is a controversy about the  $\gamma$ -ray excess in the direction of Reticulum II. Compared with the Pass 8 data, the  $\gamma$ -ray excess from Reticulum II based on Pass 7 data analysis is more significant [39–41]. The Fermi-LAT collaboration declare that this difference is because of the improvement of data Pass 8 compared with Pass 7 [41].

The newly discovered dSphs have been surveyed as point-like sources in looking for  $\gamma$ -ray signals, due to the lack of spatial extension information of DM halo. In Ref. [43], the astrophysical factor versus integration angle of Reticulum II has been performed, which can be used to deduce the spatial extension information. In this study, we search for possible  $\gamma$ -ray emission from Reticulum II, supposing it is either a point-like source or an extended source with different spatial extension. We also study the constraints on the DM annihilation cross sections from the Fermi-LAT observation of Reticulum II.

This paper is organized as follows. In sec. II, we analyze the Fermi-LAT data in the direction of Reticulum II with different spatial extension and give out the upper limits of energy flux. In sec. III, we constrain the DM annihilation cross section by the  $\gamma$ -ray emission observation of Reticulum II. Sec. IV is the summary.

## II. DATA ANALYSIS

Our work is based on the Science Tools version v10r0p5. We employ approximately 7-year Fermi-Lat data recorded from August 2008 to June 2015 with the Pass 8 photon data selection in the analysis. The events from the Pass 8 SOURCE-class in the energy band between 500 MeV and 500 GeV are adopted. In order to reduce the  $\gamma$ -ray contamination from the earth limb, the events with zenith angles larger than  $100^\circ$  are rejected, and the recommended filter cut ( $DATA\_QUAL > 0, LAT\_CONFIG == 1$ ) are applied. We create  $10^\circ \times 10^\circ$  square region as the ROI around the dSph center into  $0.1^\circ$  pixels and 8 logarithmical bins of energy from 500 MeV to 500 GeV. We use the Galactic  $\gamma$ -ray diffuse model *gll\_iem\_v06.fit* and the isotropic extragalactic  $\gamma$ -ray diffuse spectrum *iso\_P8R2\_SOURCE\_V6\_v06.txt* as the diffuse background. The third LAT source catalog (3FGL) [44] is taken to deal with the point  $\gamma$ -ray sources. In the analysis, we carry out a global fit over the entire energy range and then fix all the background sources (both point-like and diffuse) in each energy bin. The instrument response functions (IRFs) *P8R2\_SOURCE\_V6* have been set corresponding to the above LAT data selection.

Within each energy bin, the putative  $\gamma$ -ray signal of dSph Reticulum II is modeled as power-law ( $dN/dE \propto E^{-\Gamma}$ ) with spectral index of  $\Gamma = 2$ . The spatial map for extended source is indispensable, which is indicated by the DM density profile. The double integration of squared DM density along the line-of-sight and over the solid angle is called  $J$  factor, i.e.,

$$J = \int J_\Omega d\Omega = \iint \rho^2(l, \Omega) dl d\Omega. \quad (1)$$

The solid angle  $\Delta\Omega$  can be expressed as  $\Delta\Omega = 2\pi \times [1 - \cos(\alpha_{int})]$ , where  $\alpha_{int}$  is the integration angle. In Ref. [43], the DM density profile of Reticulum II is reconstructed by using an optimized spherical Jeans analysis of kinematic data obtained from the Michigan/Magellan Fiber System. They gave out the relationship of integration angle  $\alpha_{int}$  and  $J$  factor, some typical values are listed in Table I.

TABLE I.  $J$  factor for Reticulum II

$\alpha_{int}$ (deg)	$\log_{10}(J(\alpha_{int}))$ ( $\log_{10}[\text{GeV}^2\text{cm}^{-5}]$ )
0.1	$18.8^{+0.6}_{-0.5}$
0.5	$19.6^{+1.0}_{-0.7}$
1	$19.8^{+1.2}_{-0.9}$

According to the result of integration angle  $\alpha_{int}$  versus  $J$  factor, we get the relation of  $\alpha_{int}$  versus  $J_\Omega$ , which implies the spatial extension information, seen as Fig. 1. It should be noted that  $J_\Omega$  is the un-integrated astrophysical factor over the solid angle  $\Delta\Omega$ , as denoted in

Eq. 1. According to Fig. 1, we construct three different spatial maps for Reticulum II by three different degree of extension,  $0.1^\circ$ ,  $0.5^\circ$ , and  $1^\circ$ , respectively.

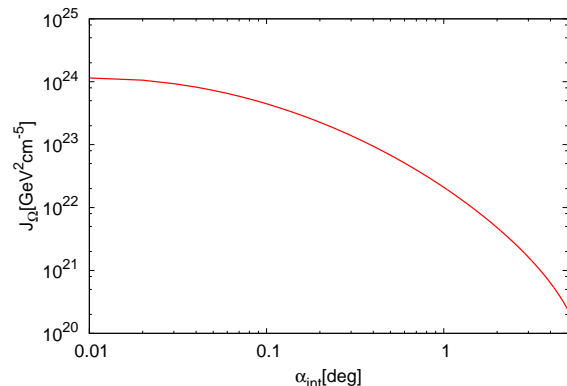


FIG. 1. Un-integrated astrophysical factor of Reticulum II, as a function of integration angle.

Following the procedure of Ref. [45], we fit for the  $\gamma$ -ray signal in each energy bin separately to derive the flux constraints that are independent of specific spectral model. We show the integrated flux upper limits at 95% confidence level (CL) in Fig. 2. Reticulum II is modeled as point-like source and three different degree of extended sources respectively in Fig. 2. From this figure, we can see that the slight  $\gamma$ -ray flux excess is mainly concentrated in the second energy bin (i.e., energy from 2.8 GeV to 6.7 GeV).

We test for  $\gamma$ -ray signal by a set of DM masses from 2 GeV to 10 TeV (when kinematically allowed) annihilating to six different channels respectively ( $e^+e^-$ ,  $\mu^+\mu^-$ ,  $\tau^+\tau^-$ ,  $u\bar{u}$ ,  $b\bar{b}$ , and  $W^+W^-$ ). The test statistic (TS) value of  $\gamma$ -ray emission signal excess over background can be obtained by comparing the likelihood values with and without additional  $\gamma$ -ray source. We find that in the set of DM mass we selected, the DM mass with 25 GeV annihilation to  $\tau^+\tau^-$  channel contributes the most significant excess, although the significance is only about  $2\sigma$ . In this case, different spatial types result in different TS values, as listed in Table II.

TABLE II. TS values for different spatial types

Spatial type	TS value
Point-like	5.46
Extend $0.1^\circ$	5.96
Extend $0.5^\circ$	6.46
Extend $1^\circ$	4.85

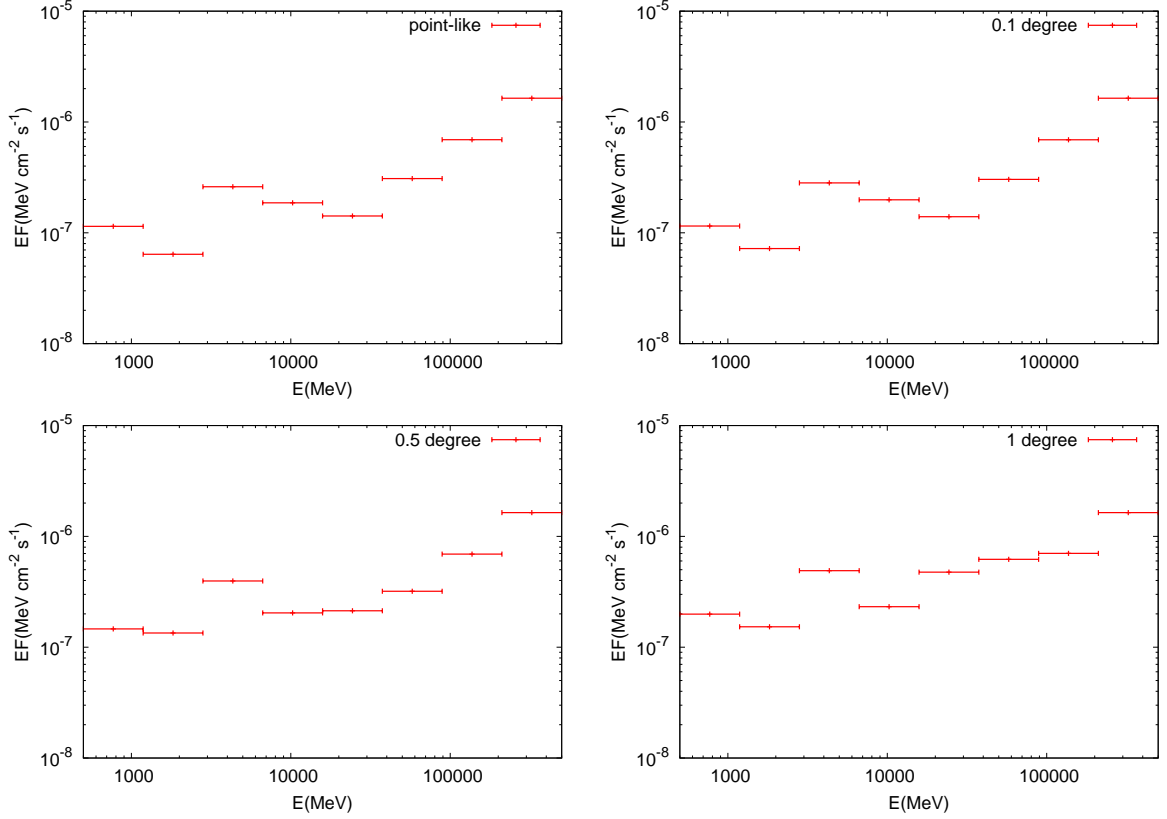


FIG. 2. Integrated flux upper limits of Reticulum II at 95% CL for point-like and spatially extended source assumption.

### III. DM ANNIHILATION CROSS SECTION

In spite of no significant  $\gamma$ -ray emission excess from the direction of Reticulum II was found, the DM annihilation cross section upper limits can be deduced. We derive the DM annihilation cross section from Reticulum II via  $e^+e^-$ ,  $\mu^+\mu^-$ ,  $\tau^+\tau^-$ ,  $u\bar{u}$ ,  $b\bar{b}$ , and  $W^+W^-$  channels. The expected integrated  $\gamma$ -ray signature flux from dSph DM annihilation can be expressed as

$$\Phi(E) = \frac{\langle\sigma v\rangle}{8\pi m_{DM}^2} \times \int \frac{dN_\gamma}{dE_\gamma} dE_\gamma \times J, \quad (2)$$

where  $\langle\sigma v\rangle$  is the thermally averaged annihilation cross section,  $m_{DM}$  is the DM mass,  $\frac{dN_\gamma}{dE_\gamma}$  is the differential  $\gamma$ -ray spectrum in one DM pair annihilation, and  $J$  is the astrophysical factor expressed as Eq. 1. Note that  $\frac{dN_\gamma}{dE_\gamma}$  should be a sum of the photons from all possible DM annihilation final states according to the DM model. Here we only consider the  $\gamma$ -ray contribution from a certain annihilation channel by PPPC [46, 47]. Strictly speaking, more stringent DM annihilation cross section upper limits should be derived by the combined analysis of all the dSphs, or at least the ones with largest  $J$  factor. We use the DM annihilation cross section derived by this dSph aims to see the differences result from various spatial extension assumptions.

We follow the method as Ref. [45, 48] to analyze the  $\gamma$ -ray emission for Reticulum II. A likelihood map is constructed, which depicts the likelihood values vary with the integrated flux  $\Phi(E)$  in each energy bin. For a certain set of  $m_{DM}$ ,  $\langle\sigma v\rangle$  and  $J$  factor inputs, the combined likelihood in all energy bins for Reticulum II can be estimated as the following equation

$$L = \prod_i L_i(\Phi_i|D) \times \frac{1}{\ln(10)J_{obs}\sqrt{2\pi}\sigma} e^{-[\log_{10}(J) - \log_{10}(J_{obs})]^2/2\sigma^2}, \quad (3)$$

where the subscript  $i$  denotes the  $i$ -th energy bin,  $\Phi_i$  is the  $\gamma$ -ray signature flux from DM,  $J_{obs}$  is the calculated  $J$  factor with an error of  $\sigma$ . For a given  $m_{DM}$  and  $\langle\sigma v\rangle$ , the  $J$  is chosen to make the likelihood value  $L$  reach a maximum. Then we can obtain the “cross section-likelihood” table for Reticulum II. By this “cross section-likelihood” table, we are able to set the upper limit on flux at 95% CL and find the value of  $\langle\sigma v\rangle$  by requiring that the corresponding log-likelihood has decreased by  $2.71/2$  from its maximum [49, 50]. For different spatial extension of Reticulum II, the constraints on DM annihilation cross section via different annihilation channels are shown in Fig. 3. From this figure, we can see that in general, when this dSph is supposed as point source, the deduced DM annihilation cross section upper limits are the most strin-

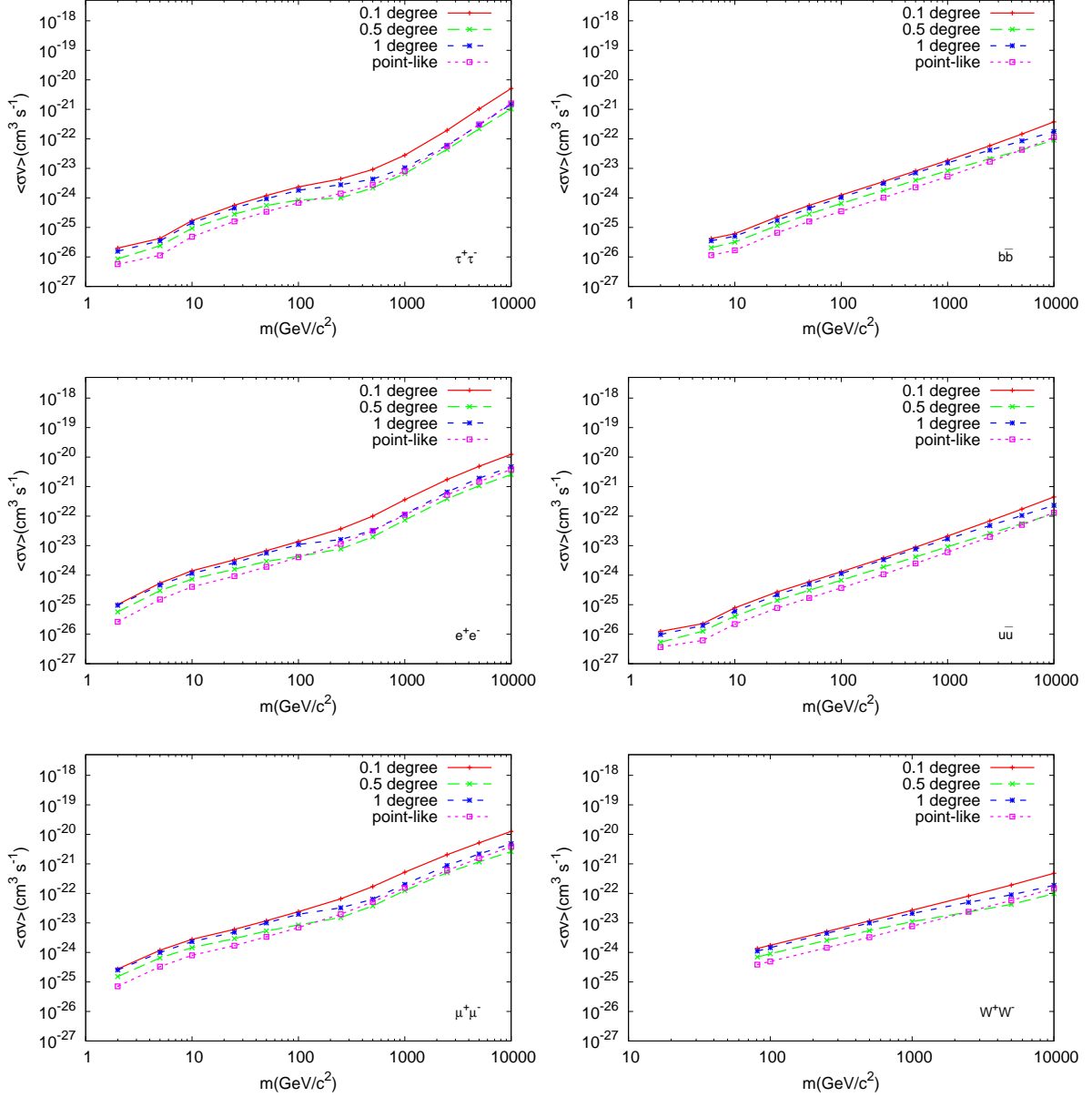


FIG. 3. Constraints on the DM annihilation cross section at 95% CL for six annihilation channels from about 7-year Fermi-LAT observation of Reticulum II. This dSph is modeled as both point-like source and three different types of spatially extended source.

gent compared with extended source assumptions. Take the  $\tau^+\tau^-$  annihilation channel for instance, the cross section upper limit from 0.1° extension assumption is higher than that from point source assumption by a factor of  $\sim 3$ .

#### IV. CONCLUSION AND DISCUSSIONS

Since the 16 new dSphs have been discovered by the optical imaging data from Dark Energy Survey, some works [39–42] have been done in searching for  $\gamma$ -ray emission from these candidates by Fermi-LAT. No significant  $\gamma$ -

ray emission has been found among these dSphs, except for the two dSphs Reticulum II and Tuc III, showing a very weak excess over background. There was a controversy on the  $\gamma$ -ray excess for Reticulum II. The excess from the analysis of Fermi data version Pass 7 is more significant than the analysis of data version Pass 8, which is due to the improvement of new data version declared by Fermi-LAT collaboration. These dSphs are modeled as point-like sources in previous studies.

In this work, we survey the  $\gamma$ -ray emission on Reticulum II from the data version Pass 8 of Fermi-LAT, supposing this dSph is a point-like source and an extended

source with different spatial extension. There is a weak excess of  $\gamma$ -ray at about 2.8 GeV - 6.7 GeV. Different spatial types result in different excess, but varies little. The DM mass at about 25 GeV annihilating to  $\tau^+\tau^-$  channel shows the largest TS value at about 5-6, depending on the spatial type. It seems that there is no obvious relationship between the TS value and the degree of extension, which may due to the complicated background. From the constraints on the DM annihilation cross section, we can see that the point-like source assumption has a stringent constraints than the extended source assumption.

Lately in Ref. [51], they surveyed all the new discovered dSphs. They point out that another two dSphs

Indus II and Tuc IV also have a slight excess with significance  $\sim 2\sigma$ . All the dSphs are modeled as point-like sources because most of the physical DM halo sizes surrounding these targets are not well constrained yet.

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